TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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FULL-SCALE SPAN LOAD DISTRIBUTION ON A TAPERED WING WITH SPLIT FLAPS OF VARIOUS SPANS

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Washington
February 1937

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SUMMARY

Pressure-distribution tests were conducted in the full-scale wind tunnel on a 2:1 tapered U.S.A. 45 airfoil equipped with 20 percent chord split trailing-edge flaps of various spans. A special installation was employed in the tests utilizing a half-span airfoil mounted vertically above a reflection plane. The airfoil has a constant-chord center section and rounded tips and is tapered in thickness from 18 percent c at the root to 9 percent c at the tip. The aerodynamic characteristics, given by the usual dimensionless coefficients, are presented graphically as functions of flap span and angle of attack as well as by semispan load diagrams. The results indicate, in general, that only a relatively small increase in the normal-force coefficient is to be expected by extending the flap span of an airfoil-flap combination, similar to the one tested, beyond 70 percent of the wing span.

INTRODUCTION

Prerequisite to the accurate design and structural analysis of a wing incorporating flaps is a complete knowledge of the aerodynamic properties of the combination. A reasonable amount of detailed information on the effect of split trailing-edge wing flaps upon the section characteristics of an airfoil is available, notably the full-scale investigation reported in reference 1. Information regarding the effect of flap span on the span-load distribution is lacking at present, although an additional investigation is under way to provide more detailed information similar to that reported herein. The data included in the present report are the results of pressure measurements made along the span of a 2:1 tapered U.S.A. 45 airfoil equipped with 20 percent chord split trailing-edge flaps of various spans.

The results presented were incidentally derived during other tests of the airfoil. Hence the results as presented are not so comprehensive as desirable; however, they provide interesting and useful data, which justify their presentation in view of the inadequacy of information of this nature.

APPARATUS

Airfoil.- The airfoil used in this investigation (fig. 1) is the starboard half-span portion of the 2:1 tapered U.S.A. 45 airfoil described in reference 2. The full-span airfoil has a span of 45.75 feet, an aspect ratio of 6.20, a mean chord of 7.38 feet, and an area of 337.50 square feet. The ordinates of the root section of the airfoil, thickness 18 percent, are given in table I. Pressure orifices are installed in the airfoil (reference 2) at the lateral locations shown in figure 1.

Split-type trailing-edge wing flaps (figs. 2 and 3) extending 35.5, 71.0, and 97.6 percent of the semispan from the plane of symmetry were installed on the airfoil. The plywood flaps, tapered in plan form, were hinged at 80 percent of the wing chord. A flap-chord to wing-chord ratio of 0.2 was maintained for all flaps and all sections along the flap span. No pressure orifices were installed on the flaps.

Inasmuch as the airfoil used was primarily designed for operation without flaps, the ailerons were designed without consideration of future flap installation. For this investigation, the aileron slots were therefore covered for all tests except for a comparison of the half- and full-span airfoils without flaps.

Reflection plane.- The half-span airfoil was mounted vertically above a reflection plane, which intersected the airfoil at the plane of symmetry (figs. 2 and 3). The reflection plane consists of a number of wooden panels bolted together to form a plane surface, 30 feet wide by 49 feet long, tangent to the lower surface of the entrance cone.

Manometers.- Two multitube liquid manometers were used to record simultaneously the individual orifice pressures. A detailed description of the manometers and

their operation is given in reference 2. The pressure tubes from the orifices to the manometers were collected within the airfoil and were not exposed to the air stream.

Tunnel.- The tests were conducted in the N.A.C.A. full-scale wind tunnel. A description of the tunnel and auxiliary apparatus is given in reference 3. Figures 2 and 3 are photographs of the airfoil with flap installation mounted vertically in the tunnel above the reflection plane.

TESTS

In order to substantiate the validity of the test results reported herein, a comparison with the full-span airfoil results reported in reference 2 was made. Pressure-distribution tests, preliminary to the main flap investigation, were made on the half-span airfoil. The test conditions of the full-span airfoil tests, other than the manner of support, were reproduced. The main investigation consisted of measurements of pressure distribution over the half-span airfoil as a plain airfoil and as one provided with flaps of three spans, each flap being set at two angles.

All tests were made at a Reynolds Number of approximately 3,800,000, based on the mean chord of the airfoil (7.38 feet). Four manometer exposures, providing four separate and distinct sets of instantaneous pressure measurements over the airfoil, were made at each of four angles of attack throughout the normal-flight range. The four pressure measurements, at each pressure orifice, were averaged in plotting the section pressure diagrams. Throughout the investigation the condition of 0° yaw and 0° roll for the airfoil was maintained.

RESULTS

Pressure measurements were limited solely to the pressures on the wing inasmuch as the flaps were not equipped with pressure orifices. The measured pressures therefore indicate the load upon the wing, including the effect of the flap upon the wing, and not the total load upon the wing-flap combination.

In order to obtain values of total load, the data presented in reference 1 were used. The ratios of flap load to wing load, from reference 1, were applied directly to the present tapered-wing results. This procedure is believed to be reasonably accurate for the angle-of-attack range investigated inasmuch as both series of tests were made with 20 percent chord flaps and under similar test conditions. The data from reference 1 are presented as section characteristics and have been directly applied. Although it is known that this procedure is not without error, owing to the effect of airfoil thickness upon the flap characteristics, an error as large as 25 percent in the determination of the flap load will cause an error of only 6 percent in the total wing-flap combination load. This method of obtaining the total load will cause larger errors in the case of the longitudinal center-of-pressure location and the pitching-moment coefficient; hence these characteristics are qualitative rather than exact.

Prior to the pressure-distribution tests, surveys of the velocity and the air-stream angle were made with the reflection plane in place. Figure 4 shows the variation in dynamic pressure above the reflection plane and on a vertical center line of the tunnel coincident with the 25 percent chord line of the airfoil.

The test results are presented graphically in the form of dimensionless coefficients. All results have been corrected for the influence of the jet boundary and for the effect of blocking (references 4 and 5). Local air-stream angles and dynamic-pressure corrections have been applied at each orifice station in computing the section pressure distribution. In addition to the foregoing corrections, a correction for the air-stream curvature of the jet based on the chord-jet height ratio (reference 6) has been applied only to the test data used in the comparison between the full- and half-span airfoils without flaps. In previous full-scale wind-tunnel tests this correction has been neglected since it is generally small. For comparative purposes, however, the correction was considered necessary in view of the large difference in jet height for the two test set-ups. The results of the flap investigation included herein have not been corrected for air-stream curvature as it is negligible and the manner of support was identical for all tests.

The results of the tests of the wing-flap combinations are presented as plots of the normal-force and

pitching-moment coefficients and longitudinal and lateral center-of-pressure locations against angle of attack. In addition, plots of semispan load distribution, of typical section load distribution, and of other airfoil characteristics are given.

Values of the section normal-force coefficient c_n and of the longitudinal center-of-pressure locations along the section for the wing portion of the wing-flap combination were determined from section load diagrams of orifice pressure against section chord, as follows:

$$c_n = \frac{A}{qc}$$

and longitudinal center-of-pressure location from the quarter-chord point, M_A/A:

where

- A is the integrated area of the section pressure diagram.
- M_A, integrated moment of area of the section pressure diagram about the quarter-chord point of the section chord.
- c, section chord.
- q, dynamic pressure.

The section normal-force coefficient and the longitudinal center-of-pressure location along the section of the wing-flap combination were obtained from the measured pressures by applying correction factors, derived from the data of reference 1, for flap load and flap center of pressure. Typical section load diagrams are shown in figure 5 for a section 114-1/4 inches outboard of the wing center line. The figure shows section load diagrams, at approximately the same angle of attack, 14°, for the plain wing and for the 97.6 percent span flap deflected 20° and 60°. The pressure measurements over the wing portion of the combination are shown by the experimental points; the pressure distribution over the flap was computed.

It is necessary to use a factor other than c_n to represent the span-load distribution on tapered wings because the chord of the wing varies along the span. Plots

of the relative normal loadings K at the orifice stations along the span for the various test conditions are shown in figures 6 to 12. The factor K is nondimensional and is defined by

$$K = c_n \frac{\text{section chord}}{\text{semispan}}$$

Values of the wing normal-force coefficient C_N, the total pitching-moment coefficient about the root quarter-chord point, and the longitudinal and lateral center-of-pressure locations for the wing-flap combinations as derived by the pressure plots and corrected for flap load are presented in figures 13 to 16. The values of C_N, $C_{m_{c/4}}$, the longitudinal center-of-pressure location in percentage of the root chord from the leading edge of the root chord, and the lateral center-of-pressure location in percentage of the semispan from the plane of symmetry were determined as follows:

$$C_N = \frac{A'}{q\,\frac{S}{2}}; \quad \text{lateral c.p.} = \frac{M_{A'}}{A'} \times \frac{2}{b}$$

$$C_{m_{c/4}} = \frac{A''}{q\,\frac{S}{2}\,\bar{c}}; \quad \text{longitudinal c.p.} = \frac{1}{4} - \frac{C_{m_{c/4}}}{C_N} \times \frac{\bar{c}}{c'}$$

where A' is the integrated area of the semispan load diagram.

$M_{A'}$, integrated moment of area of the semispan load diagram about the plane of symmetry.

A'', integrated area of the semispan moment diagram; the section pitching moments about the quarter-chord point were computed from section c_n and c.p. positions and plotted against the semispan.

S, total airfoil area.

b, airfoil span.

$\bar{c}$, mean chord of airfoil, S/b.

c', root chord of airfoil.

The presented data have been corrected for local airstream angle and dynamic pressure as well as for wing washout and may be considered as applying to an unwarped airfoil in a uniform-velocity field. In the presentation of the data it is to be noted that the chord forces on the airfoil have been neglected; i.e., the longitudinal center-of-pressure positions and the pitching-moment coefficients were derived solely from consideration of the normal forces.

The variations of the lateral and longitudinal center-of-pressure locations are shown (figs. 17 and 18) plotted against flap span in percentage of the wing span for the two flap angles tested.

The effectiveness of extending the flap span of the 20 percent chord flaps as tested on the U.S.A. 45 airfoil is shown in figure 19 for two flap angles and for the several angles of attack investigated. This effectiveness, or relative efficiency, of added increments of flap span is defined as the rate of increase of C_N with flap span. So as not to limit the use of the curves to a specific profile or span, the effectiveness as plotted is the rate of increase of C_N, in terms of C_{N_0} (the normal-force coefficient of the plain wing at the same angle of attack), with flap span in percentage of the wing span.

DISCUSSION

Inasmuch as the size and position of the flaps in the present investigation were limited, a comprehensive analysis of the data is at present unwarranted. The presented results are, however, believed to be of an interesting and important nature and of sufficient accuracy for use in the design of similar wing-flap combinations.

Figure 5 shows the effect of the flap upon the pressure distribution over the rest of the wing chord and is similar to that shown in reference 1.

The following observations, which in general would be anticipated, are made from the semispan load diagrams given in figures 6 to 12. A marked similarity is noticeable in the shape of the loading curves for the plain wing and the wing with the 97.6 percent span flap at the same value of C_N; the effect of the flap is to shift the location of the longitudinal center of pressure aft. For

the partial-span flaps an abrupt drop in loading is encountered at the flap tip and, when compared with the plain wing at the same value of C_N, an increase or building up of load inboard and a decrease outboard of the flap tip are evidenced.

Figure 13 affords a comparison between tests of the half-span airfoil mounted vertically above a reflection plane and the full-span airfoil (reference 2), of the same profile and plan form, mounted horizontally on the wind-tunnel center line. The results of the two tests compare favorably with the exception of a 0.5° displacement of the normal-force coefficient curves. The slopes of the C_N curves are identical and the discrepancy in angle of attack may be attributed to combined errors in measuring the air-stream angle and angle of attack.

The aerodynamic characteristics of the airfoil as equipped with the flaps of different length and for flap deflections of 20° and 60° are shown in figures 14 to 18. The results are much as expected and are similar to those from previous tests of split trailing-edge wing flaps. For both flap angles tested, the location of the lateral center of pressure moves outboard with an increase in flap span, at all angles of attack investigated (fig. 17). This trend is reasonable inasmuch as the load is increased over that portion of the wing equipped with the flap, as shown by an inspection of the semispan load diagrams. For all positive angles of attack tested, the tendency of the location of the longitudinal center of pressure is to recede from the leading edge with an increase in flap span (fig. 18). This recession is generally greater for the larger flap deflection.

The effectiveness factor when plotted as shown (fig. 19) provides a means of determining the normal-force coefficient of a similar airfoil equipped with a 20 percent chord flap. An integration of the area under this curve gives the increase in C_N in percentage of the normal-force coefficient of the plain wing at the same angle of attack for any desired span of flap extending outboard from the plane of symmetry. A decided dissimilarity is noted in the curves for different flap angles, especially at low angles of attack. For large flap deflections ($\delta_f = 60°$) the effectiveness of adding to the flap decreases appreciably at high angles of attack for flap spans of more than 60 percent of the wing span; whereas at

small flap angles ($\delta_f = 20^\circ$) this effectiveness holds up well until a value of flap span equal to 70 percent of the wing span has been reached. From an inspection of figure 19 it would seem that relatively little is to be gained in normal-force coefficient by extending the flap span of an airfoil-flap combination of the type tested beyond 70 percent of the wing span.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., January 24, 1936.

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2. Parsons, John F.: Full-Scale Force and Pressure Distribution Tests on a Tapered U.S.A. 45 Airfoil. T.N. No. 521, N.A.C.A., 1935.

3. DeFrance, Smith J.: The N.A.C.A. Full-Scale Wind Tunnel. T.R. No. 459, N.A.C.A., 1933.

4. Silverstein, Abe: Scale Effect on Clark Y Airfoil Characteristics from N.A.C.A. Full-Scale Wind-Tunnel Tests. T.R. No. 502, N.A.C.A., 1934.

5. Theodorsen, Theodore, and Silverstein, Abe: Experimental Verification of the Theory of Wind-Tunnel Boundary Interference. T.R. No. 478, N.A.C.A., 1934.

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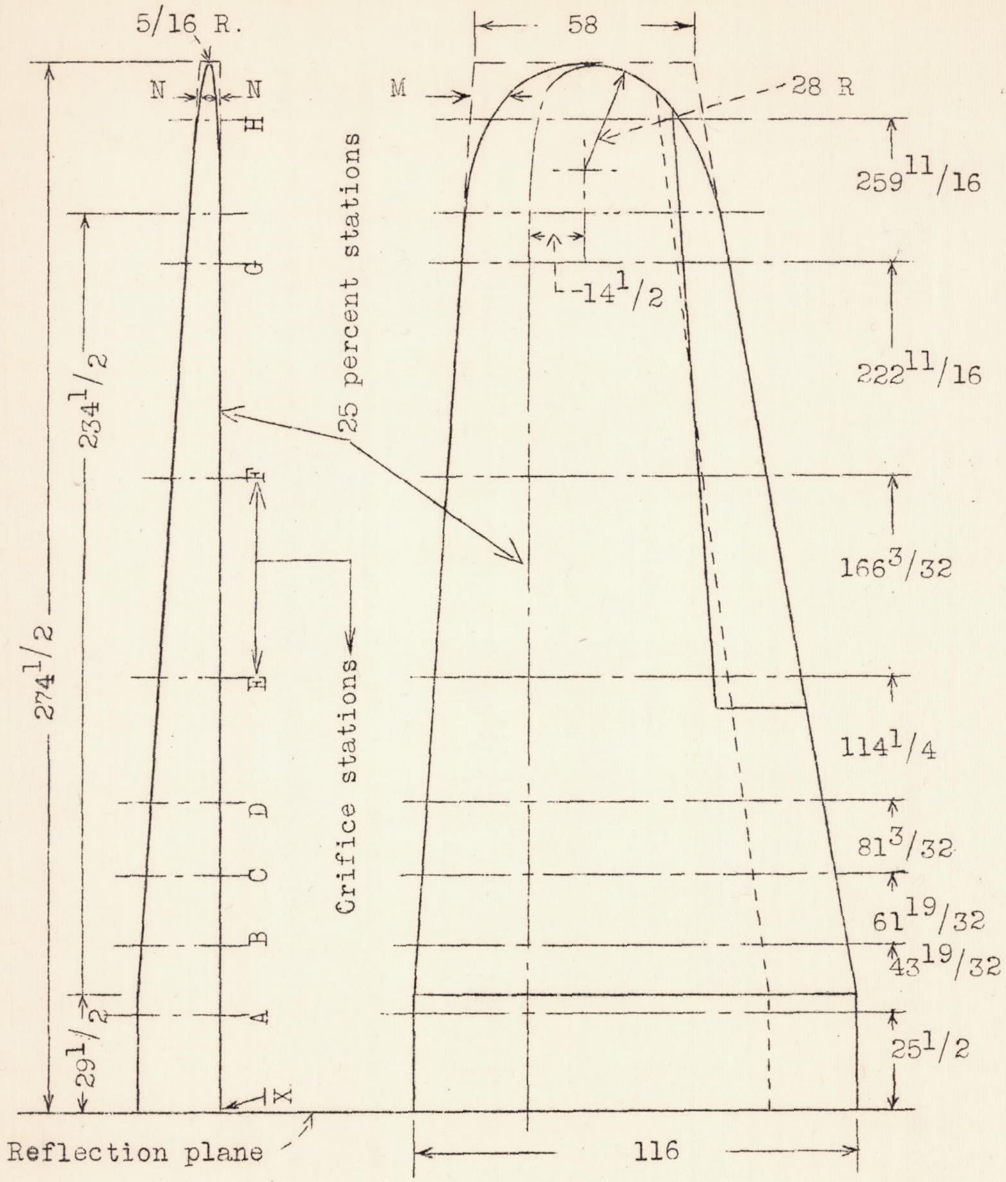
TABLE I: Tapered U.S.A. 45 Airfoil

Specified section ordinates, root section

Station	Upper	Lower
Chord, 116 inches		
Thickness, 18 percent		
0	1.63	1.63
1.25	4.71	-.04
2.5	6.20	-.67
5	8.63	-1.52
7.5	10.45	-2.05
10	11.70	-2.50
15	13.22	-3.20
20	14.11	-3.51
25	14.38	-3.62
30	14.24	-3.68
40	13.13	-3.61
50	11.08	-3.40
60	9.60	-3.00
70	7.47	-2.44
80	5.11	-1.73
90	2.59	-.92
95	1.27	-.45
100	0	0

Section ordinates in percent chord.
Stations in percent chord from L.E.



Station	Chord	M	N
234.5	67.47	0.	0.
244.5	63.70	.52	.05
254.5	56.40	2.88	.35
264.5	43.40	8.20	1.20
274.5	0	29.00	3.15
All dimensions are in inches			

Figure 1.- Half-span tapered U.S.A.45 airfoil plan form and orifice station location.

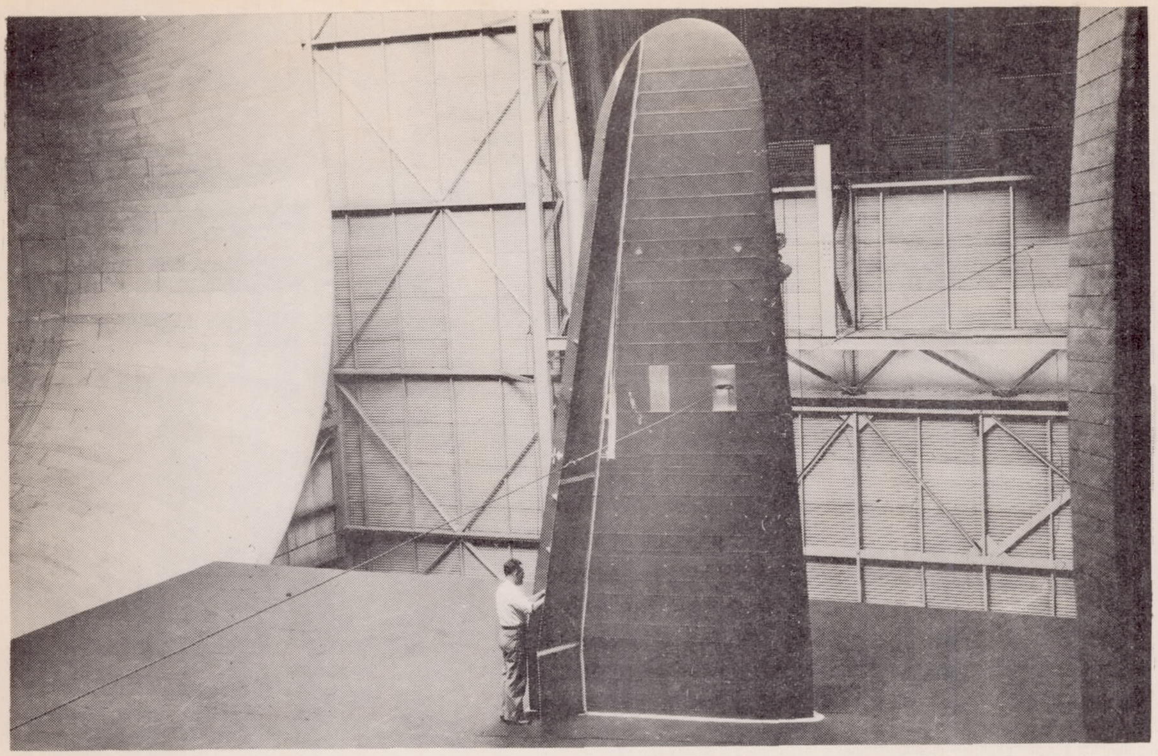


Figure 2.- Half span tapered U.S.A.45 airfoil mounted in test position. 97.6 percent span flap.

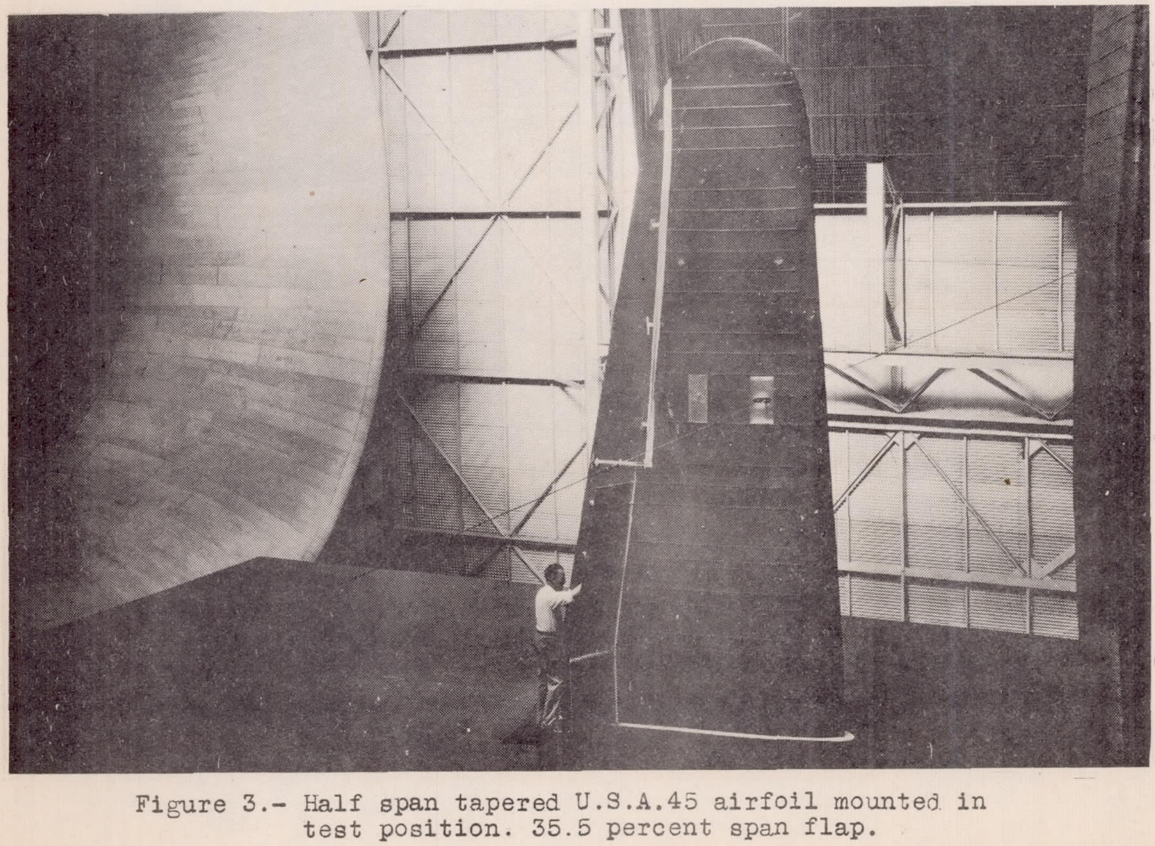


Figure 3.- Half span tapered U.S.A.45 airfoil mounted in test position. 35.5 percent span flap.

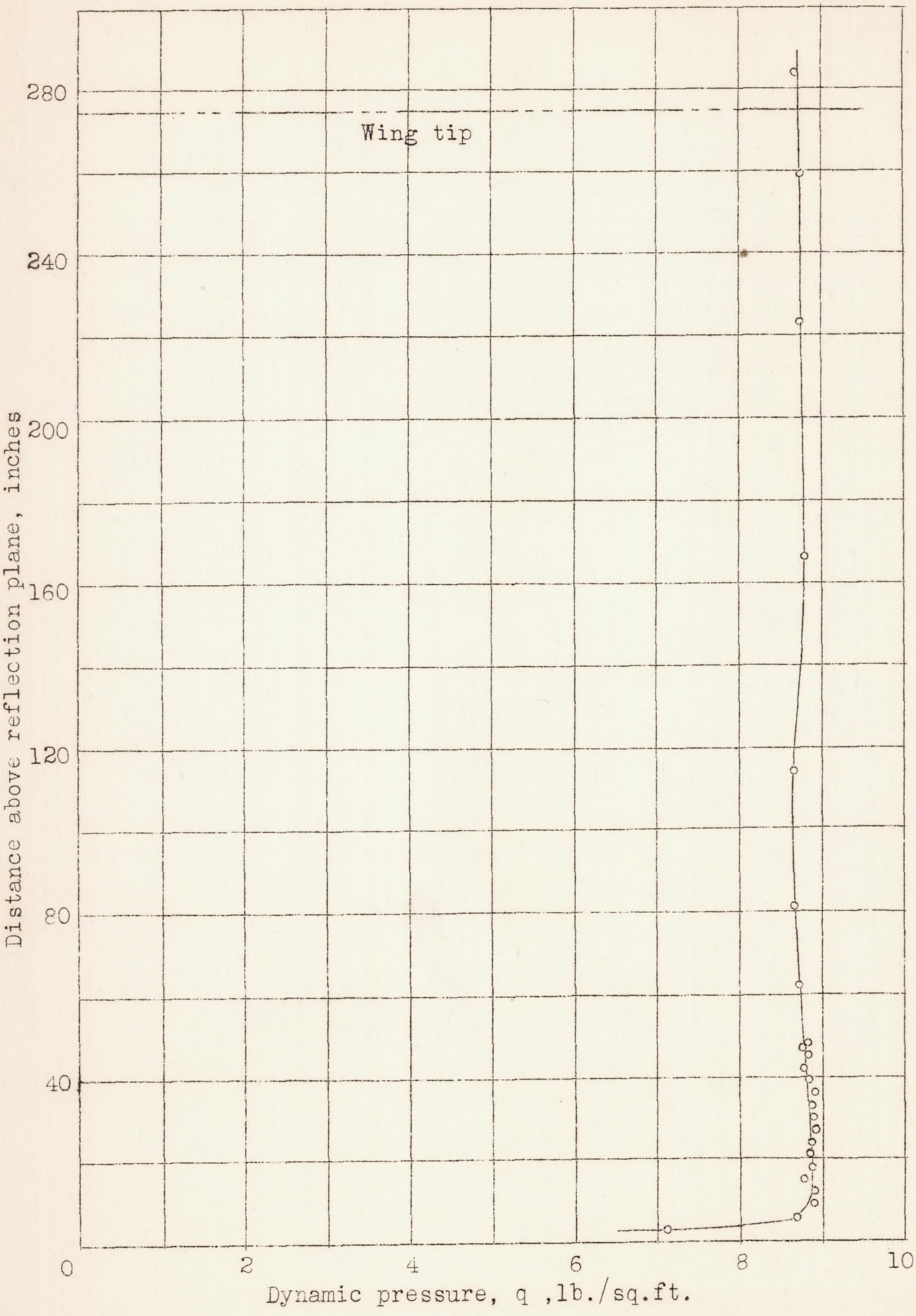


Figure 4.- Dynamic-pressure survey above reflection plane on tunnel vertical center line in plane of the airfoil.

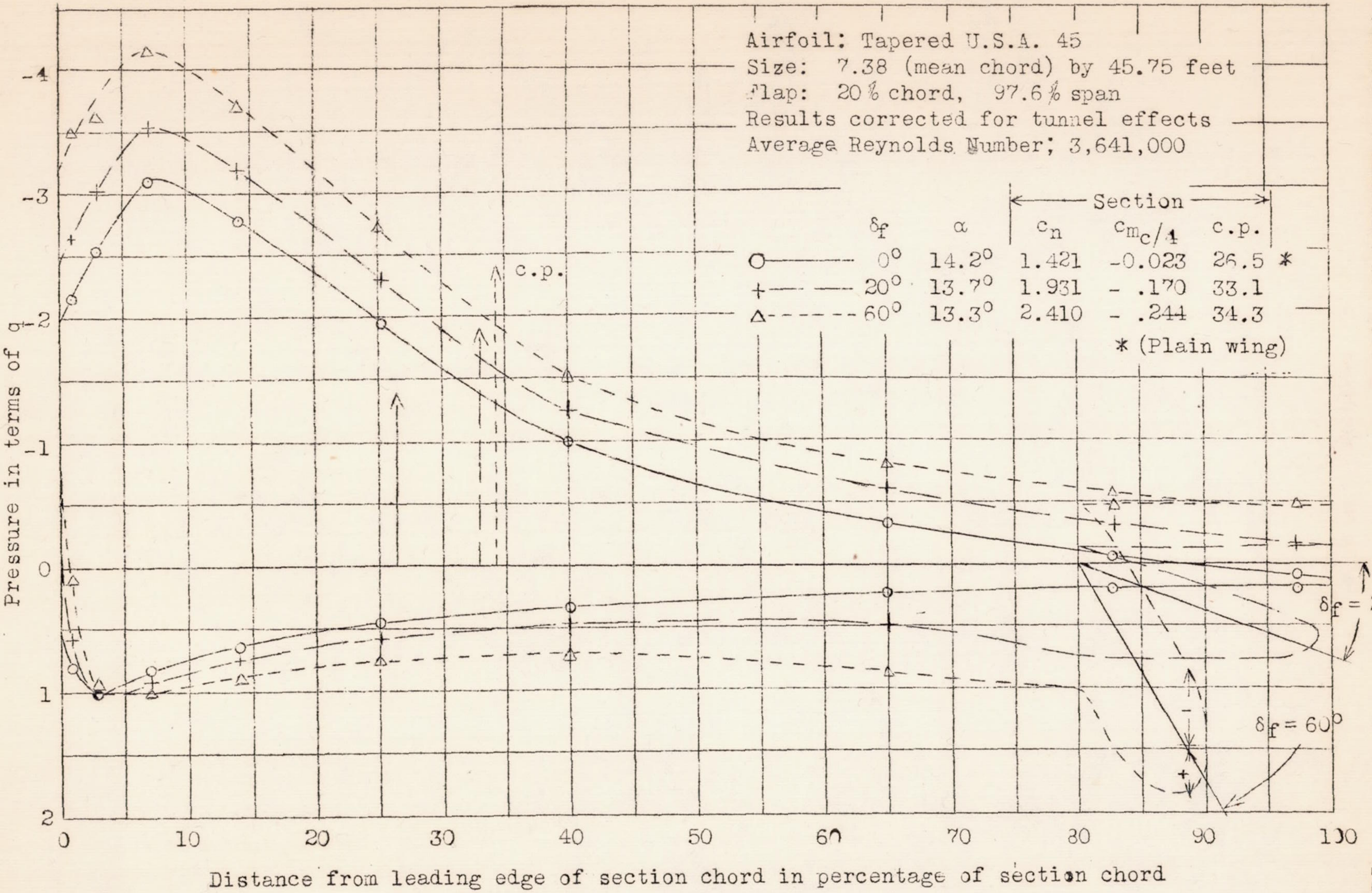


Figure 5.- Typical section pressure diagrams.

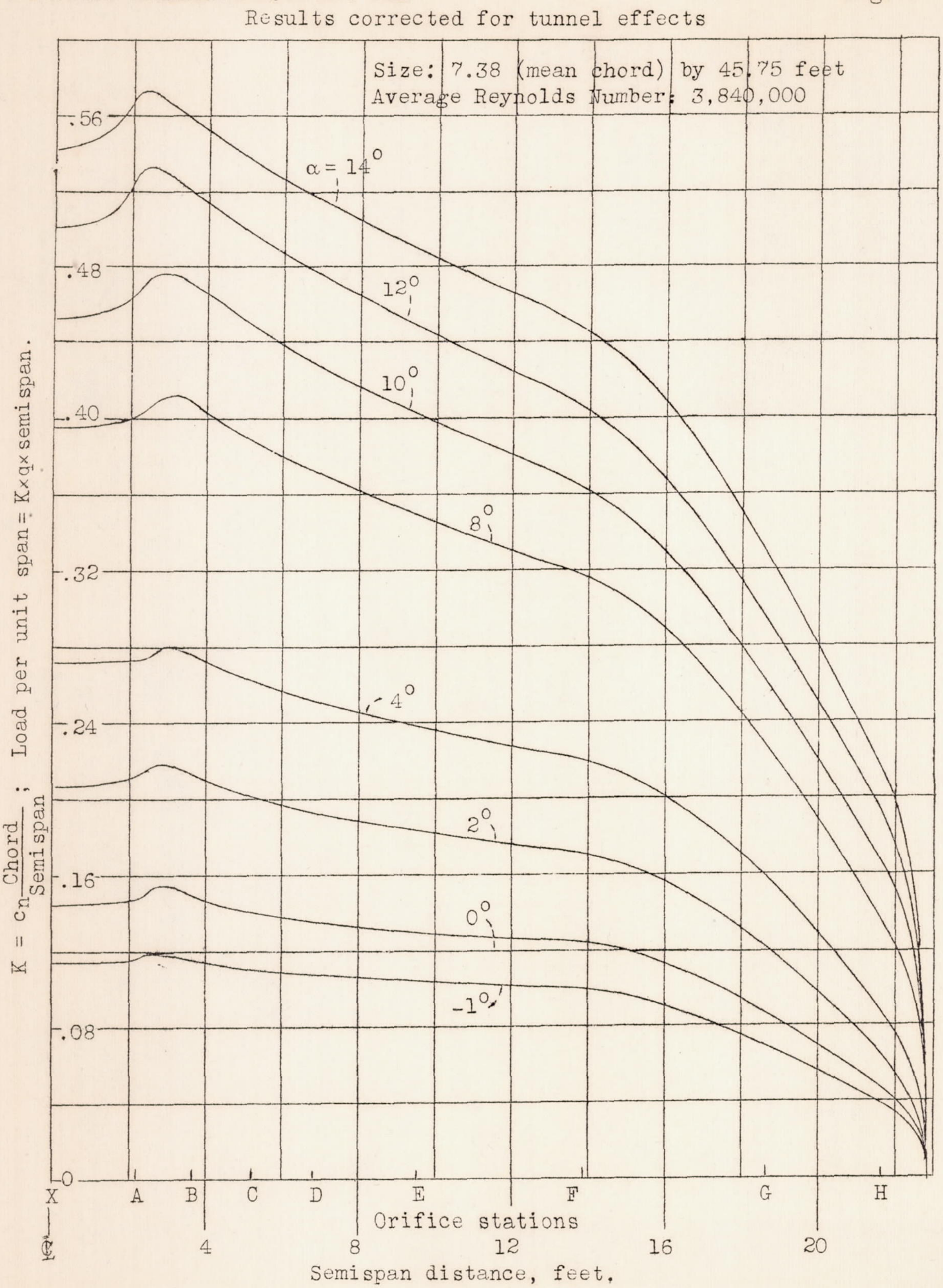


Figure 6.- Semispan load diagram of the tapered U.S.A. 45 airfoil. Plain airfoil.

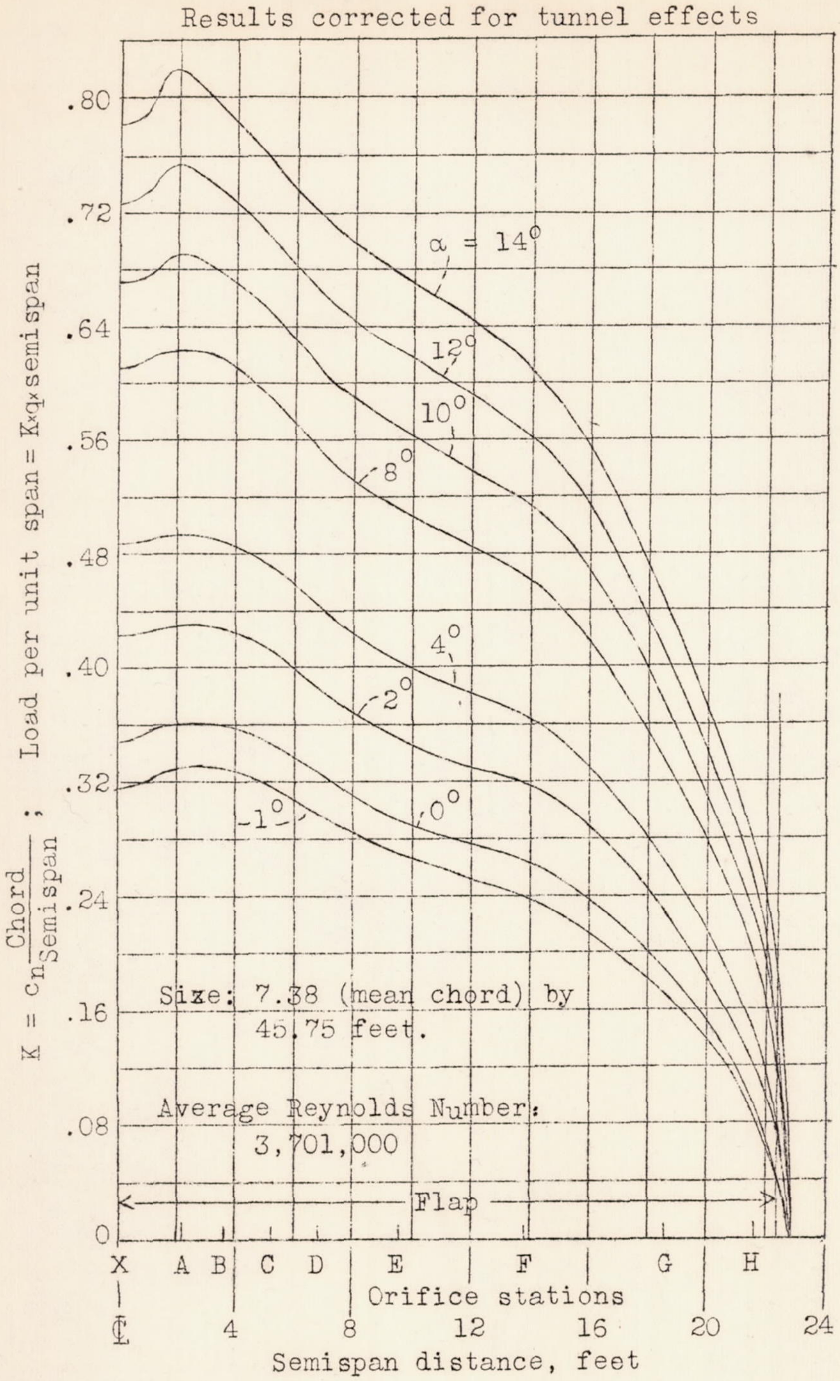


Figure 7.- Semispan load diagram of the tapered U.S.A. 45 airfoil. 20 percent chord, 97.6 percent span flap, 20° flap angle.

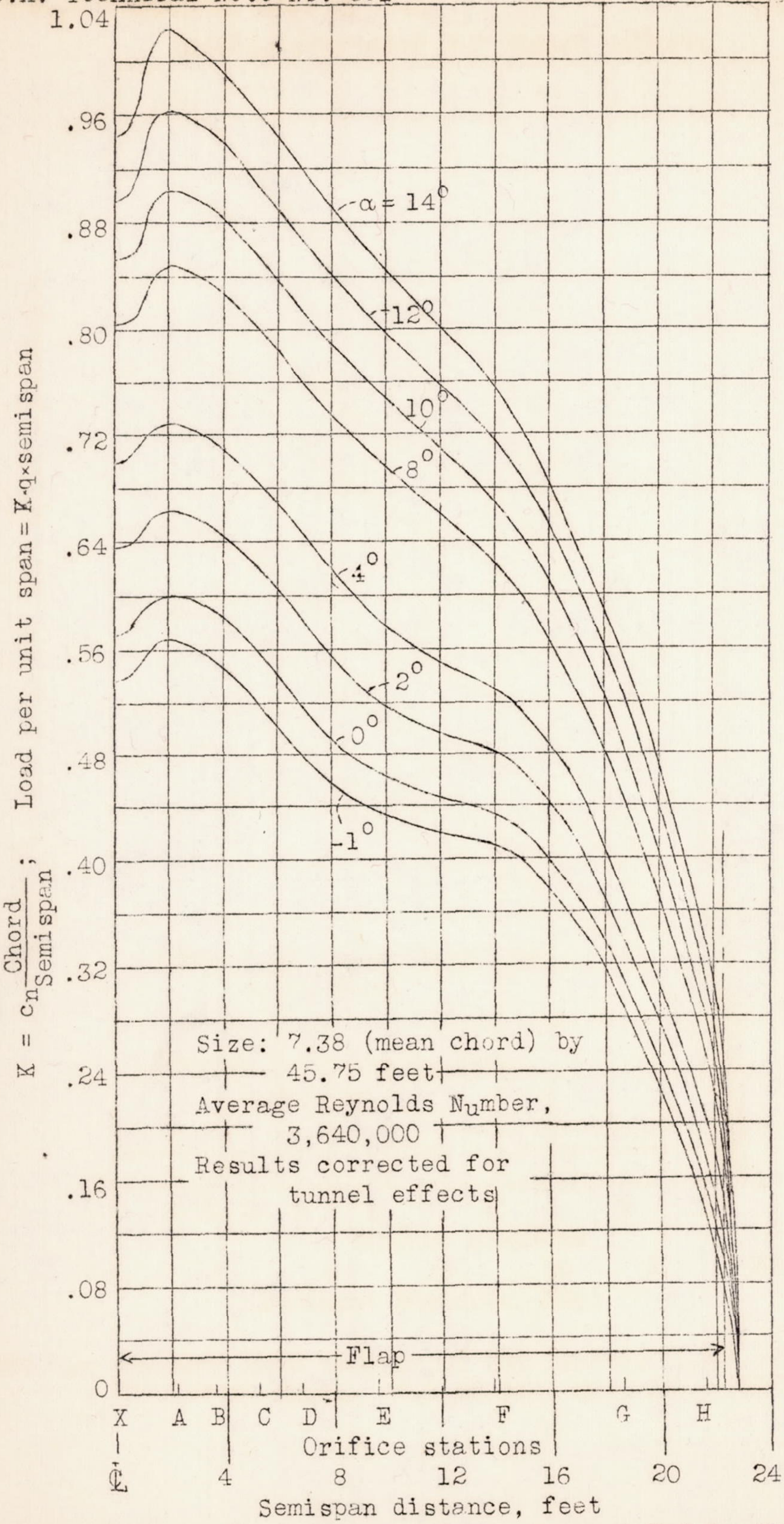


Figure 8.- Semispan load diagram of the tapered U.S.A. 45 airfoil. 20 percent chord, 97.6 percent span flap, 60° flap angle.

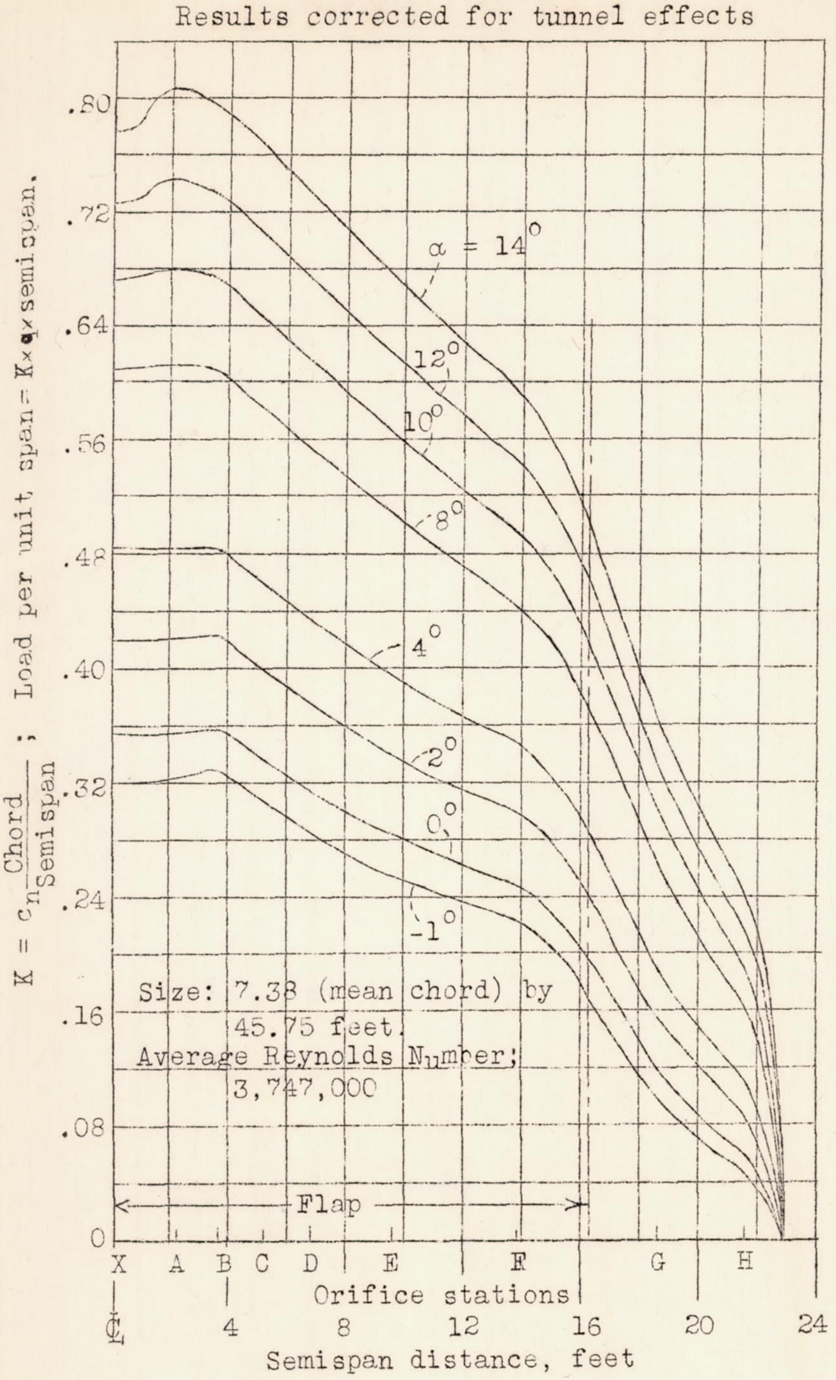


Figure 9.- Semispan load diagram of the tapered U.S.A. 45 airfoil. 20 percent chord, 71.0 percent span flap, 20° flap angle.

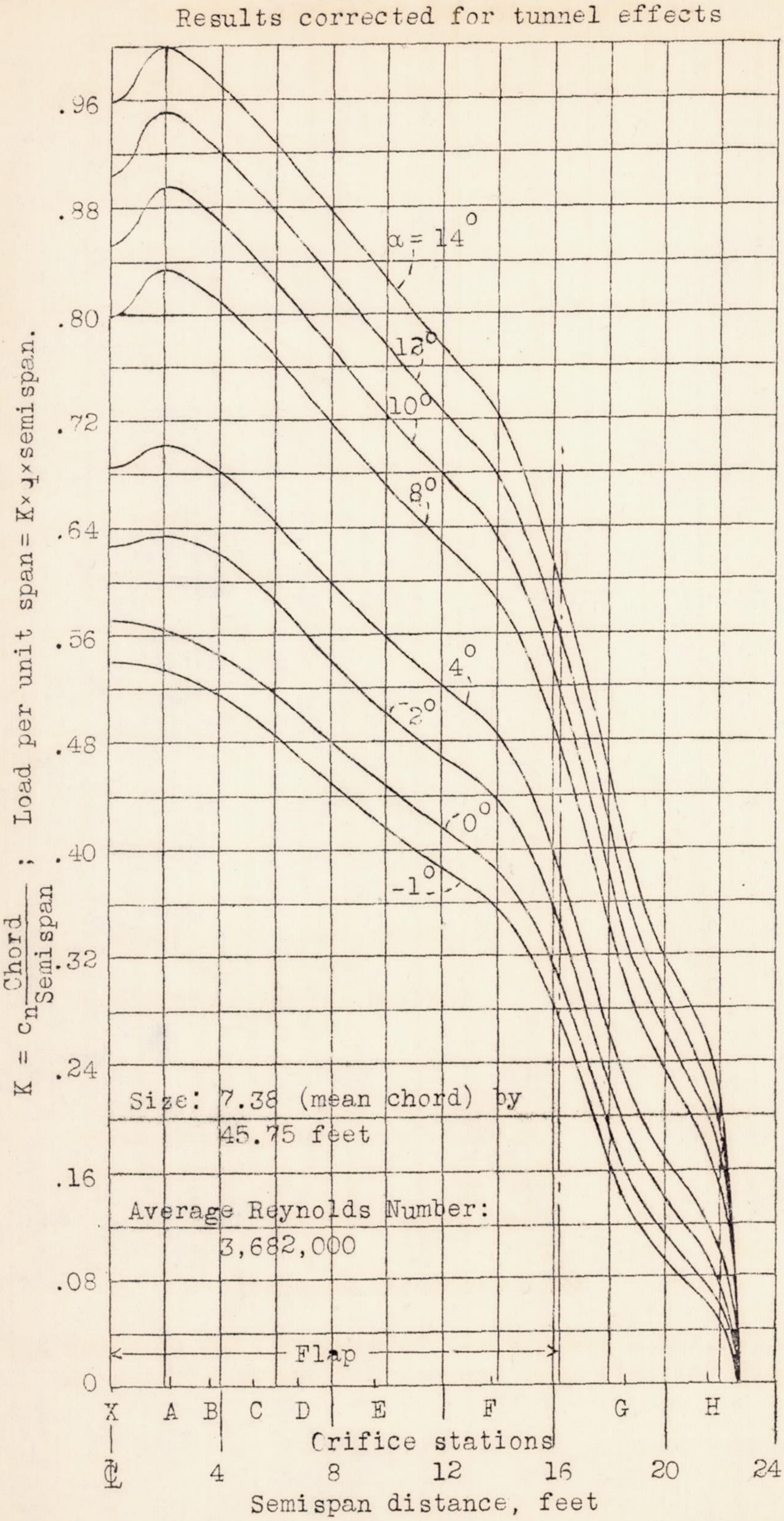


Figure 10.- Semispan load diagram of the tapered U.S.A. airfoil. 20 percent chord, 71.0 percent span flap, 60° flap angle.

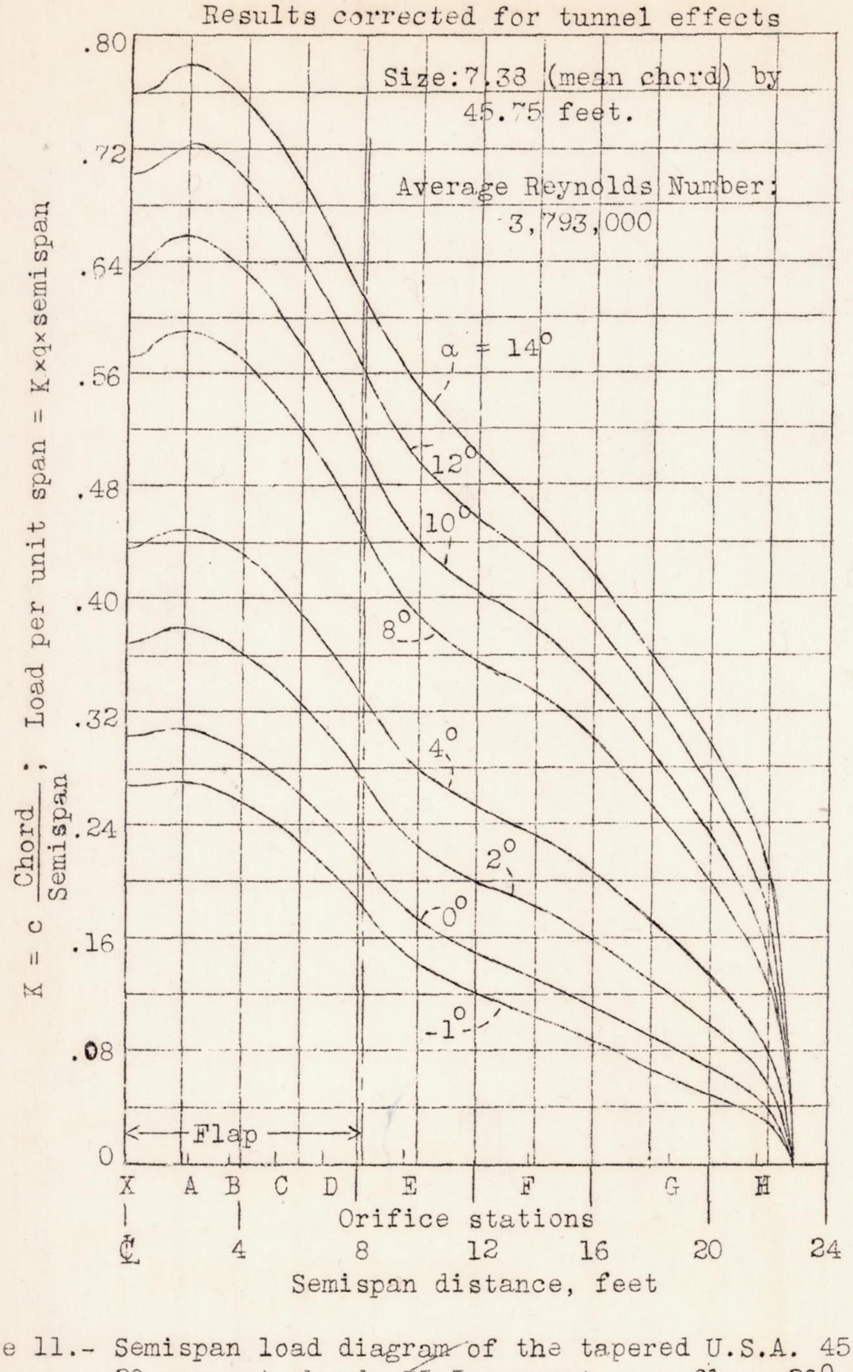


Figure 11.- Semispan load diagram of the tapered U.S.A. 45 airfoil. 20 percent chord, 35.5 percent span flap, 20° flap angle.

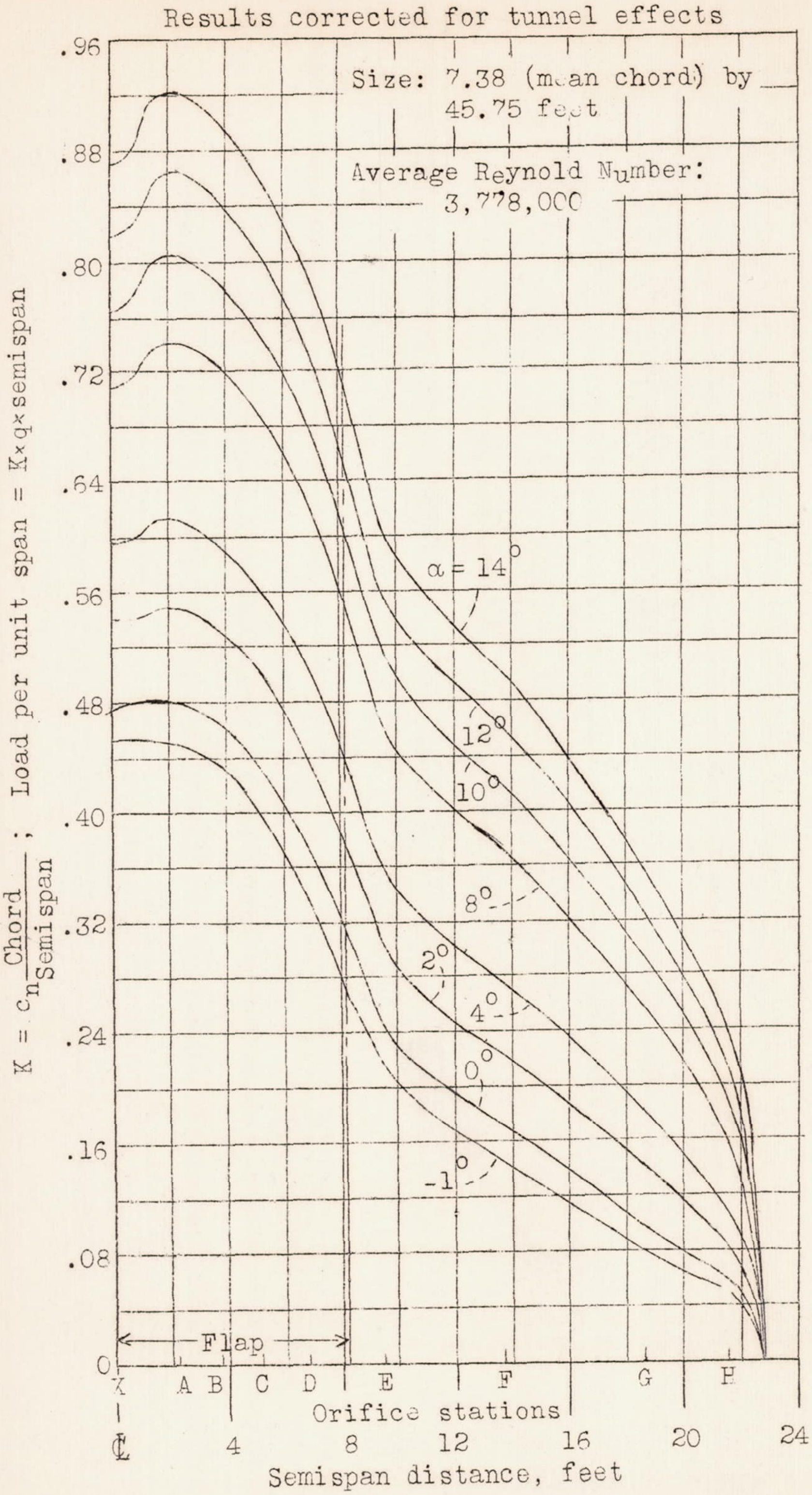


Figure 12.- Semispan load diagram of the tapered U.S.A. 45 airfoil. 20 percent chord, 35.5 percent span flap, 60° flap angle.

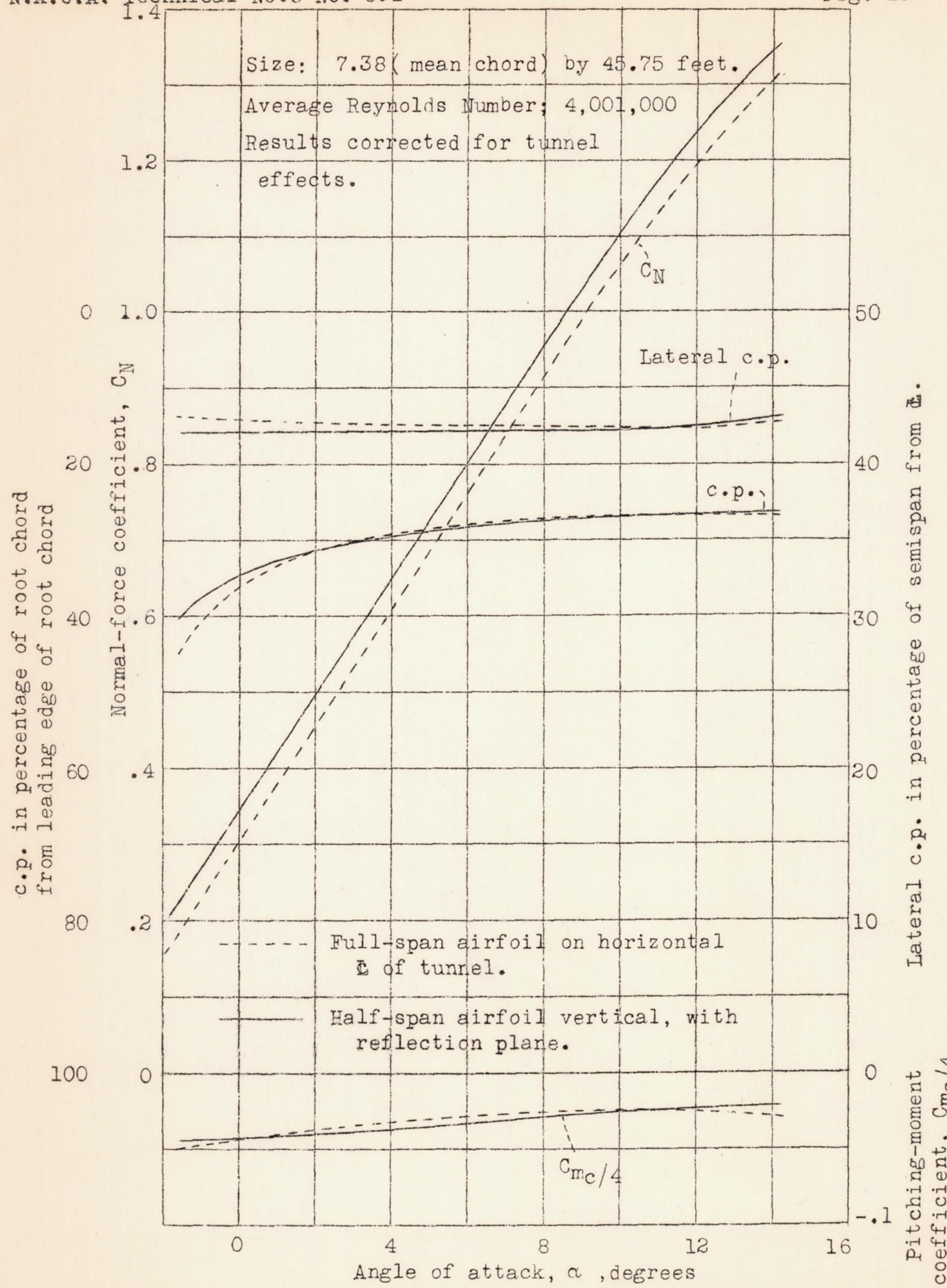


Figure 13.- Comparison of pressure-distribution tests on a half and a full-span tapered U.S.A. 45 airfoil.

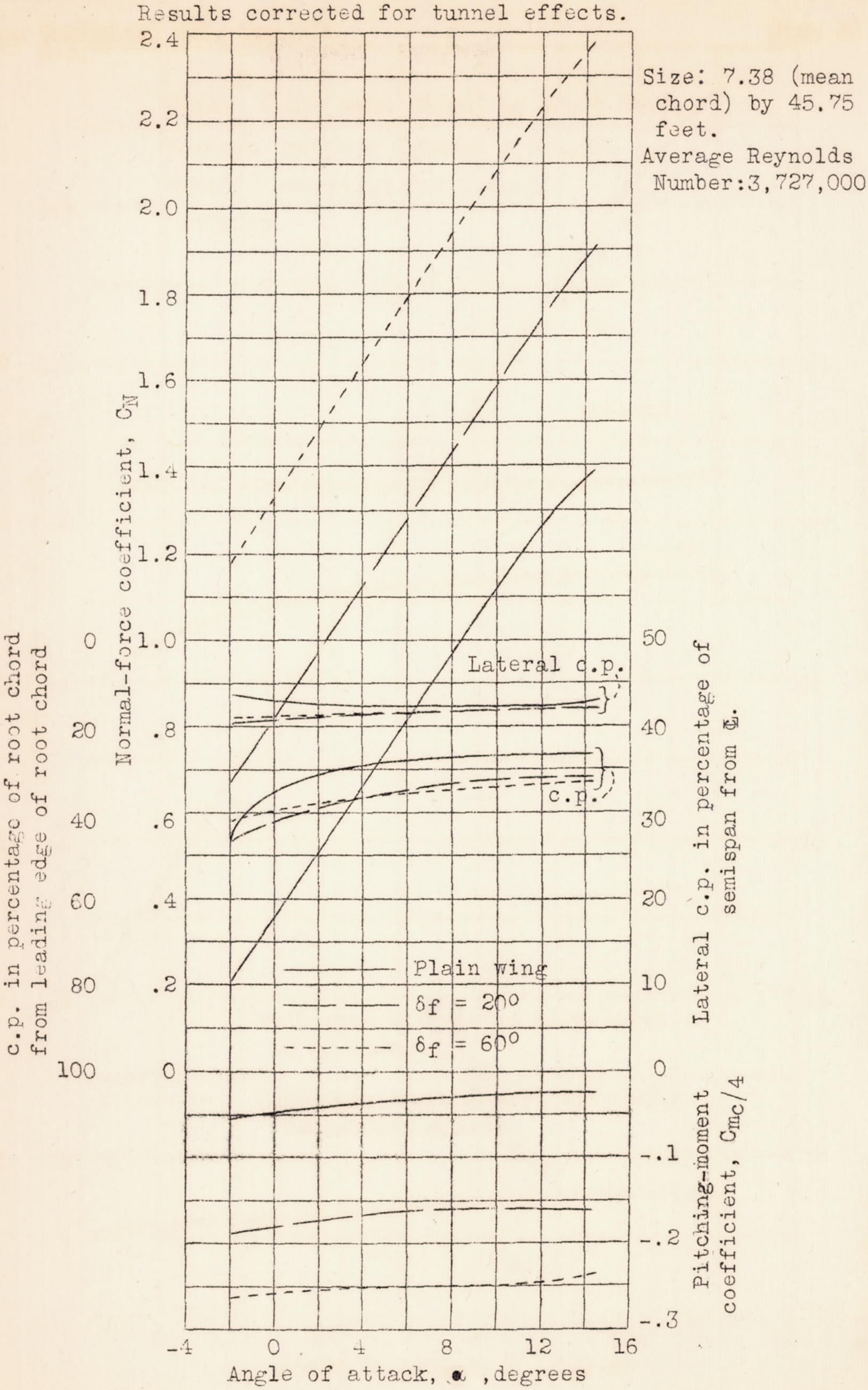


Figure 14.- The characteristics, as determined by pressure-distribution tests, of the half-span tapered U.S.A. 45 airfoil, 20 percent chord, 97.6 percent span flap.

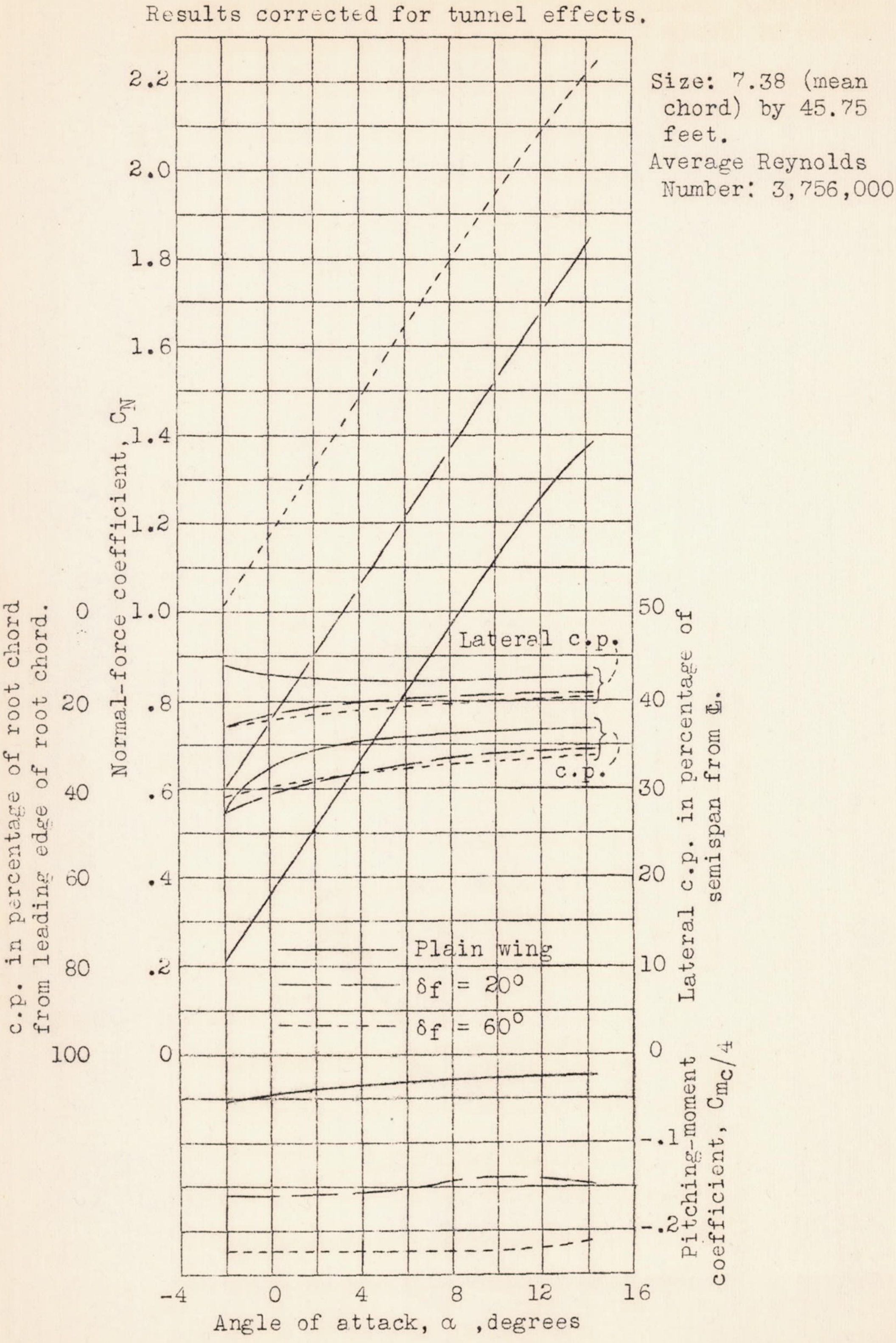


Figure 15.- The characteristics, as determined by pressure-distribution tests, of the half-span tapered U.S.A. 45 airfoil. 20 percent chord, 71.0 percent span.

Results corrected for tunnel effects.

Size: 7.38 (mean chord) by 45.75 feet.
Average Reynolds Number: 3,804,000

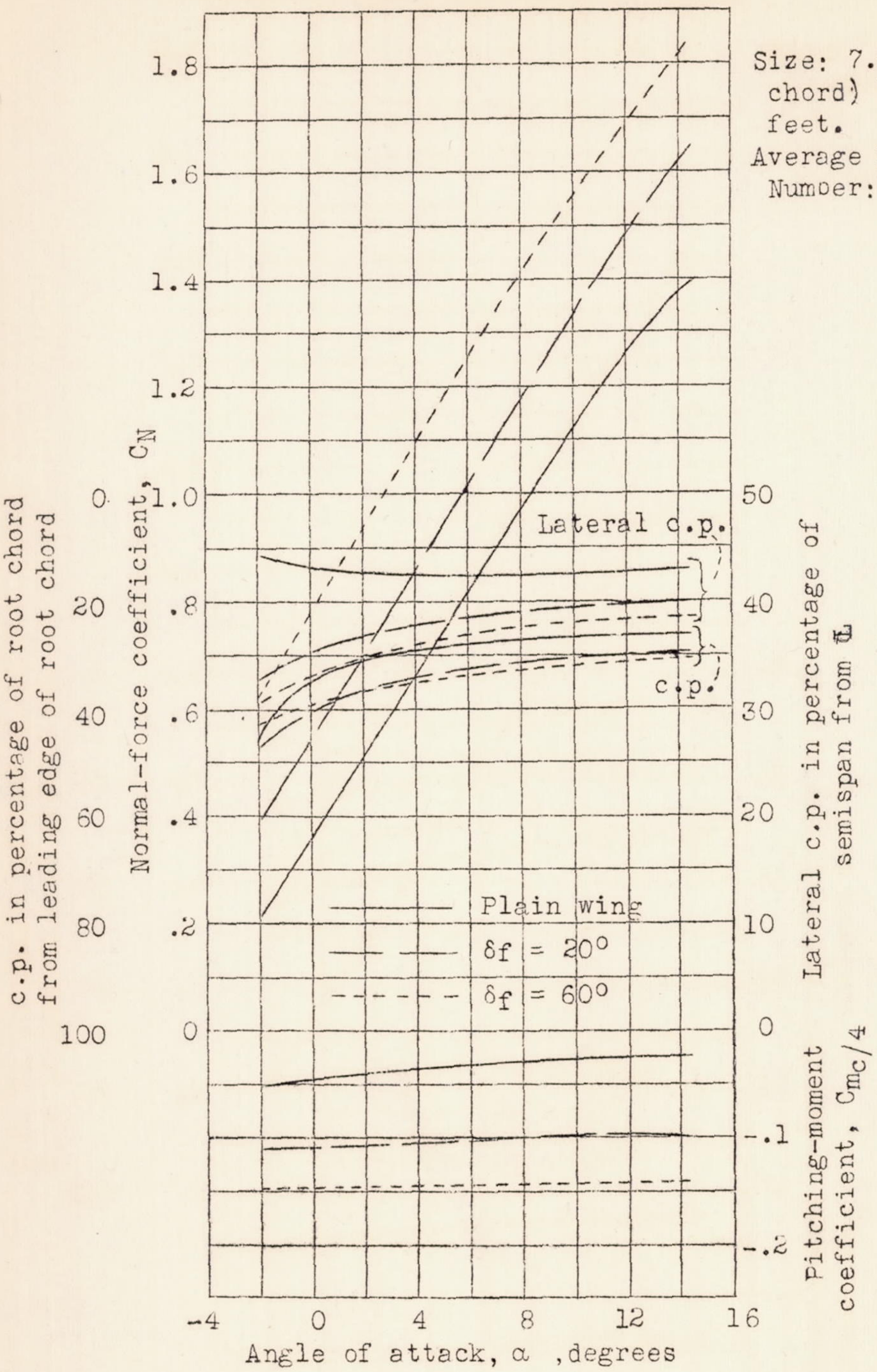


Figure 16.- The characteristics, as determined by pressure-distribution tests, of the half-span tapered U.S.A. 45 airfoil. 20 percent chord, 35.5 percent span flap.

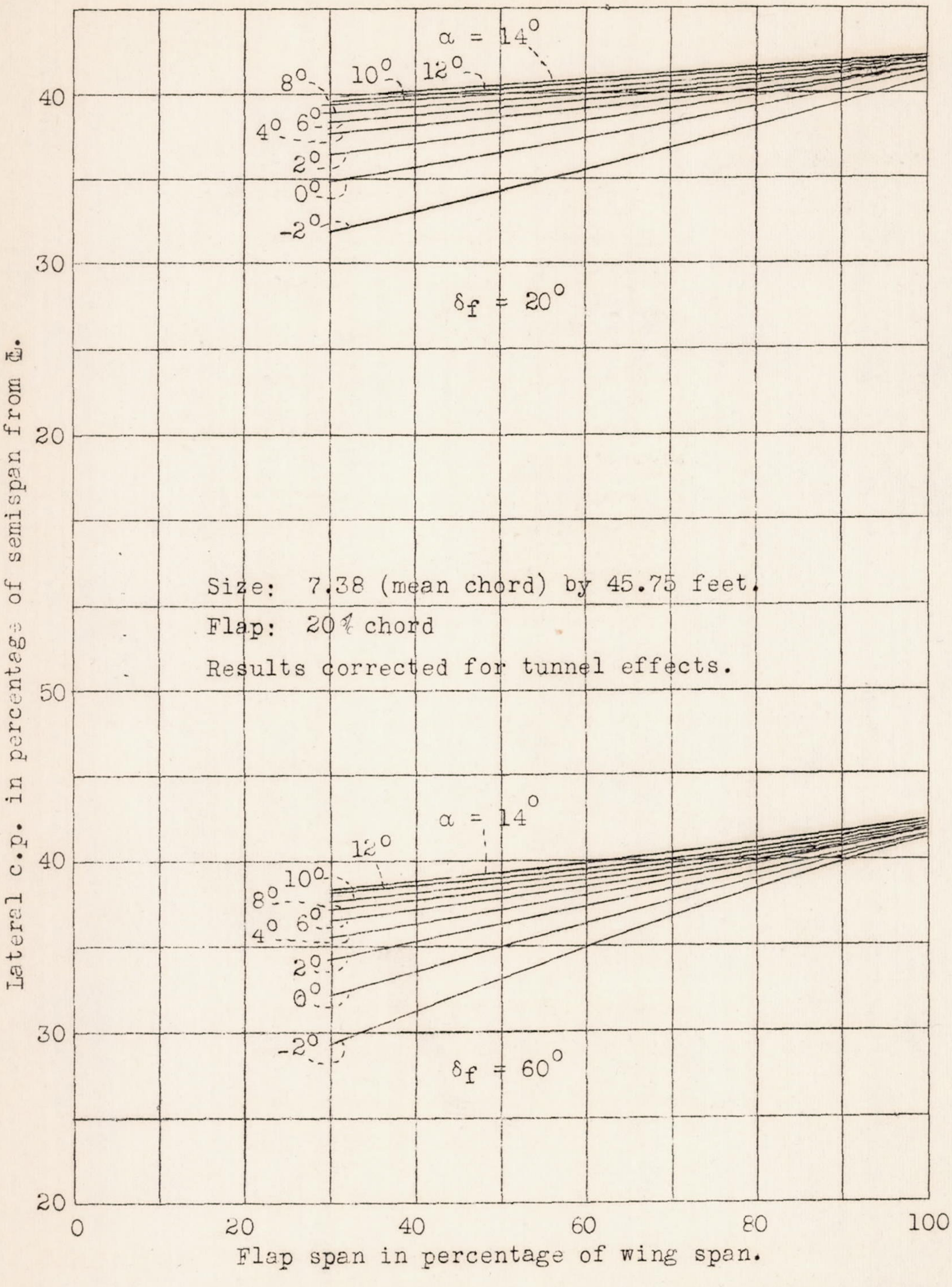


Figure 17.- Variation of lateral center-of-pressure location with flap span for the tapered U.S.A. 45 airfoil.

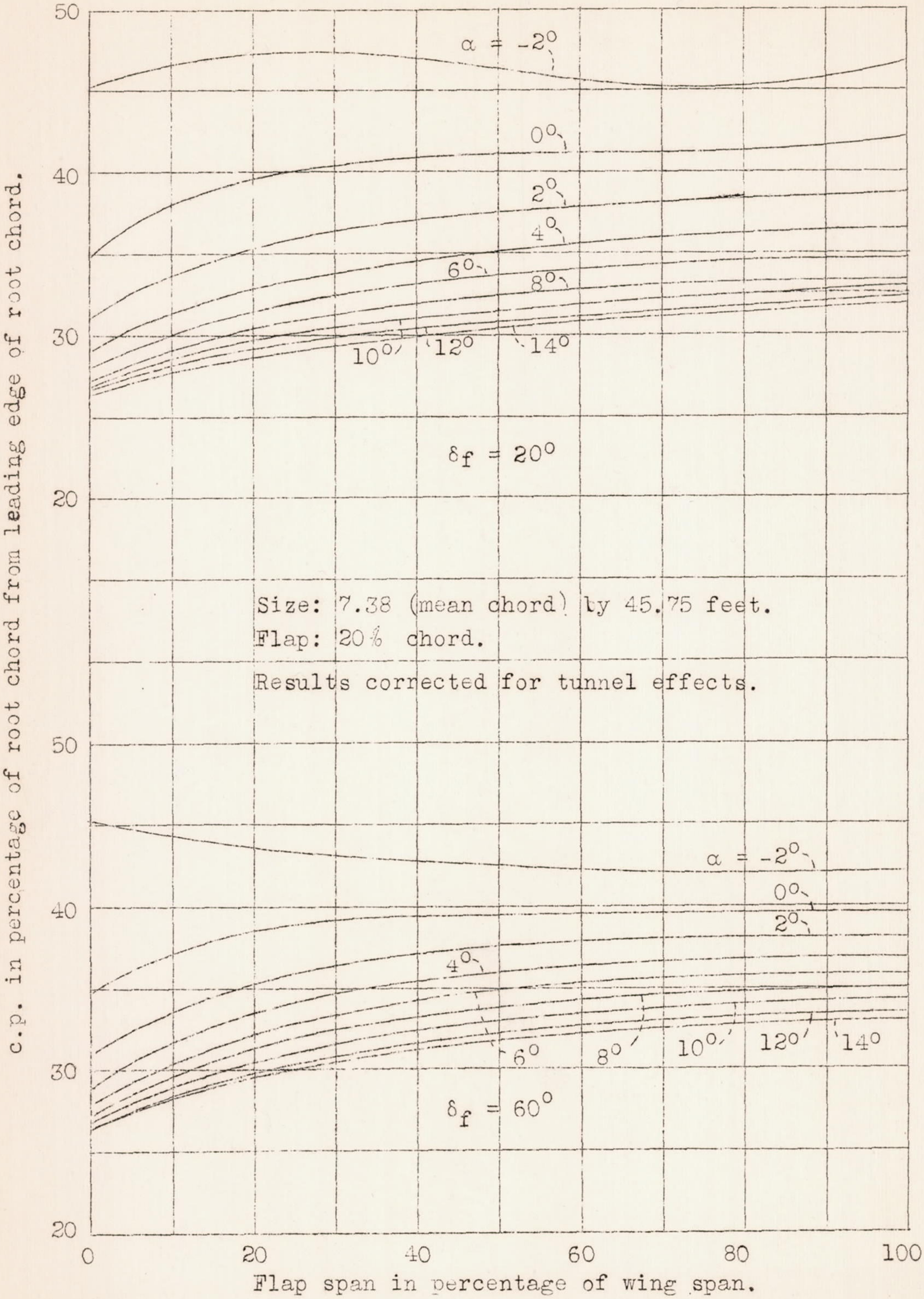


Figure 18.- Variation of longitudinal center-of-pressure location with flap span for the tapered U.S.A. 45 airfoil.

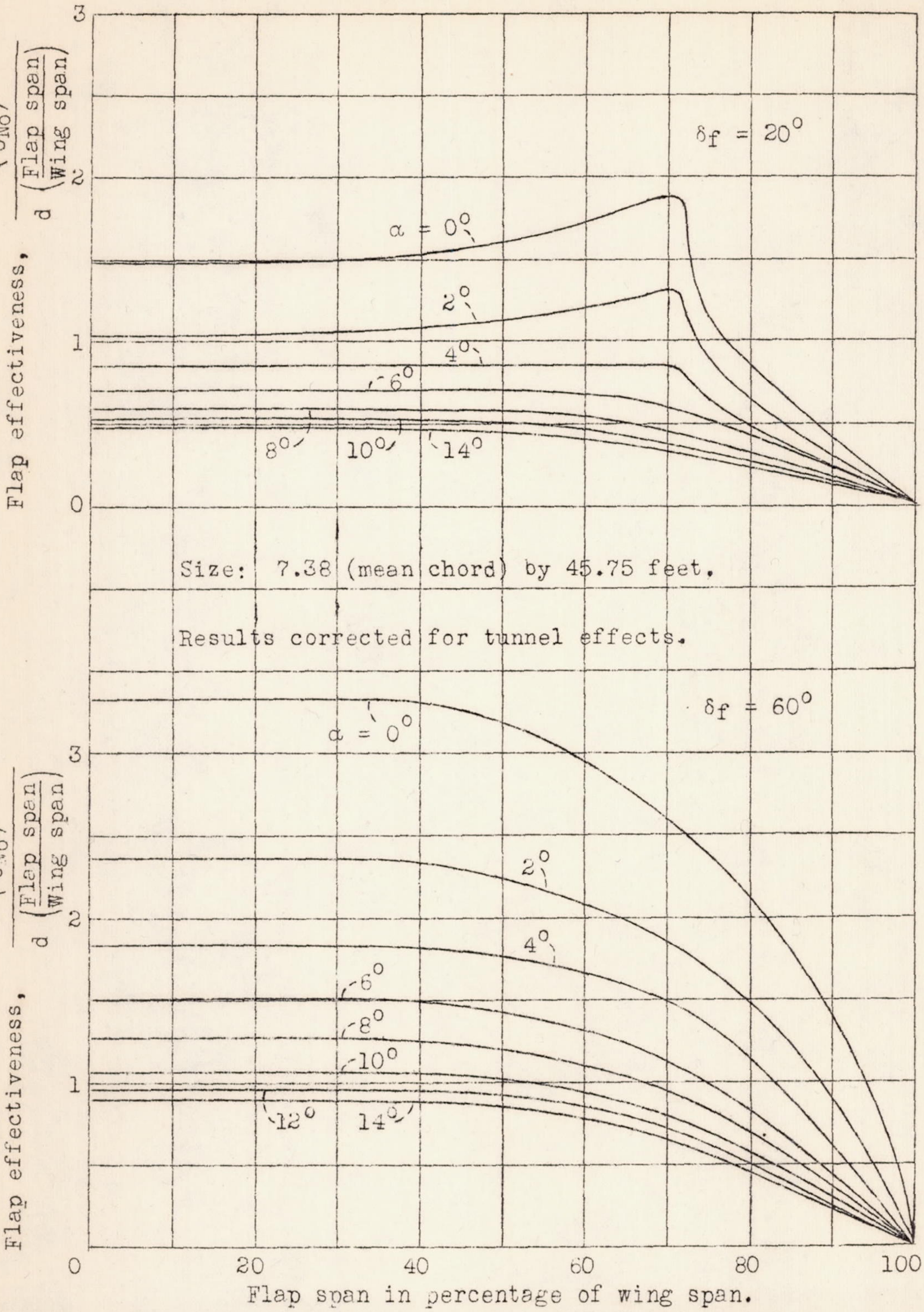


Figure 19.- Effectiveness of added increments of flap span for a 20 percent chord flap on a tapered U.S.A. 45 airfoil.